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210 days of storage in deionised water and NaCl solution. A degradation in tensile strength up to 30.2% and 10.8% was recorded for the specimens subjected to treatment in aqueous solution and to high cycle fatigue testing, respectively. This degradation indicated that extended storage in a wet environment may cause significant decreases of mechanical properties.

**Keywords:** GFRP grid; fatigue; ageing; long-term behaviour; masonry structures; composite materials.

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## **1 Introduction**

Historic masonry wall panels with in-plane loadings have been extensively investigated in the past (Vintzileou and Tassios, 1995; Binda et al., 1997; Van Rickstal, 2001), both analytically and experimentally. Because of tensile strength of masonry may be assumed to be equal to zero, researchers have studied the use of new materials and techniques to retrofit masonry constructions.

FRP materials are made of artificial or natural fibres embedded in a polymeric matrix and exhibit several characteristics which make them suitable as structural reinforcing elements. FRPs are characterised by high tensile strength in the fibres' direction and by linearly elastic response up to failure. The matrix has two principal functions: transfers the load to the fibres and protects them from degradation due to environmental effects.

Previous research indicates that FRPs may significantly enhance the mechanical behaviour of masonry structures. Triantafillou (1998) and Valluzzi et al. (2001) reinforced masonry panels using FRP laminates disposed longitudinally and horizontally to the masonry surface. Tinazzi et al. (2000) and Tumialan et al. (2001) used FRP bars to reinforce the horizontal joints of masonry walls. Recently, several researches have concentrated their attention on the investigation of new techniques to retrofit and strengthen masonry buildings using Glass Fibre Reinforced Polymers (GFRP) grids (Borri et al., 2014a; Borri et al., 2014b; Corradi et al., 2014; Gattesco et al., 2014). Alternative innovative composite materials have also been developed. For example, in an attempt to avoid problems associated with the use of epoxy resins, an innovative composite material, known as Textile Reinforced Mortar (TRM), was developed (Papanicolaou et al., 2008). TRM has been used over the last decade for seismic retrofitting of structures, particularly concrete and masonry structures (Bousias et al., 2007; Koutas et al., 2014; Koutas et al., 2015; Tetta et al., 2015). While studies have shown that TRMs are more effective in increasing the deformation capacity of structures, they are generally less effective in resisting shear compared to FRP (Tetta et al., 2015).

The static resistance of masonry structures is usually affected by their exposure to environmental changes or degrading agents, such as alkaline agents and moisture variation. The deterioration of matrices is due to hydrolysis, swelling and plasticisation in water environments. Furthermore, this makes the interface between the fibres and the matrix weak, and consequentially produces a decrement of the properties of components of the masonry structure. Although the effect of these changes on mortar matrix has been well studied in the past (Lanas and Alvarez, 2003; Lanas et al., 2005), further studies are required on the long-term behaviour of the reinforcing materials, especially when under new forms like grids or nets, not previously studied in the past.

Several studies on the use of FRP materials are limited to defining the improvements in terms of capacity and stiffness of reinforced masonry elements without due consideration of the long-term behaviour and the durability of the masonry. For example, GFRP grids, inserted into an organic matrix (lime mortar), can coexist with extremely high pH values, due to the hydration process of lime, that could potentially produce damaging of the glass fibres (Borri et al., 2014c). It is therefore fundamental to examine the effect and consequence of environmental factors on long-term performance of the FRP material. Gangarao and Vijay (1997) exposed glass and polyester composite materials samples to different treatments in water solutions. Uomoto (2003), Karbhari et al. (2003) and Liao et al. (1999) considered the susceptibility to dissolution in alkaline environment of the glass fibres. Lab studies on FRP materials exposed to different

treatments in water solutions exhibited the possibility of sudden reduction of their mechanical properties (Chu et al., 2004; Nkurunziza et al., 2005; Chen et al., 2007; Abbasi and Hogg, 2005).

For structures exposed to cyclic loads, fatigue becomes a significant limit state that necessities to be considered. It is imperative and particularly significant to obtain information about the long-term performance of FRP materials exposed to high number of load cycles in order to understand possible decay in terms of strength and stiffness of the material. The results could be extremely useful to define design life of the structural reinforcement. Decrease in strength of GFRP materials due to fatigue has been experimentally assessed by Andersons and Korsgaard (1999). Numerous studies on the fatigue effect have been carried out also on concrete beams strengthened with FRP materials (Gussenhoven and Brena, 2005; Ekenel et al., 2006; Gheorghiu et al., 2006; Brena et al., 2005).

This paper addresses the problem of the durability of GFRP grids exposed to various environmental conditions. Several specimens subjected to artificial aging treatments and to cyclic loading have been tested in order to study the degradation mechanism in terms of tensile capacity and stiffness. The experimental results, partially presented (Corradi et al., 2015), demonstrate that the mechanical properties generally decreased after ageing treatments or fatigue tests.

## 2 Material description

Two commercially available GFRP grids (Figure 1) were included in this study characterised by a mesh size of  $66 \times 66$  mm. The difference between them was in the dry glass fibre section. Grids epoxy vinyl ester resin with AR-glass (Alkali Resistant) reinforcement was used and the material was characterised by a zirconium content equal to or greater than 16%. GFRP was manufactured using unidirectional glass fibre.

Specimens were cut from GFRP grids, respectively, from the horizontal (wrap) and vertical (weft) directions, using a diamond saw in order to have four different cross-sections. SC and SR indices have been adopted to identify circular and rectangular sections characterised by a dry glass fibre section of  $3.8 \text{ mm}^2$ , while BC and BR indicated circular and rectangular sections with dry glass fibre section of  $7.6 \text{ mm}^2$ . The first two typologies have been obtained from the grid type 1 and the last two from the grid type 2. The main characteristics of GFRP specimens are summarised in Table 1.

**Table 1** Specimen detail

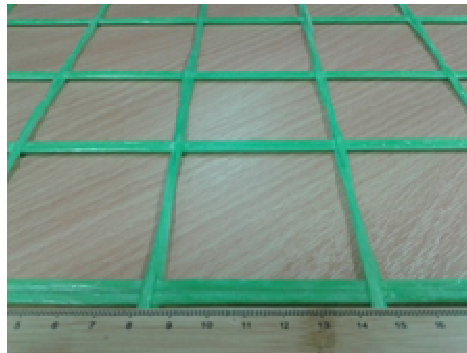
<i>Index</i>	<i>Section shape</i>	<i>Cross-section area</i>	<i>GFRP grid type</i>	<i>Length</i>	<i>Weight density</i>	<i>Direction</i>
–	–	$\text{mm}^2$	–	$\text{mm}$	$\text{g/m}^2$	–
SC	Circular	3.8	1	190	500	Weft
BC	Circular	7.6	2	190	1000	Weft
SR	Rectangular	3.8	1	190	500	Warp
BR	Rectangular	7.6	2	190	1000	Warp

### **3 Experimental program**

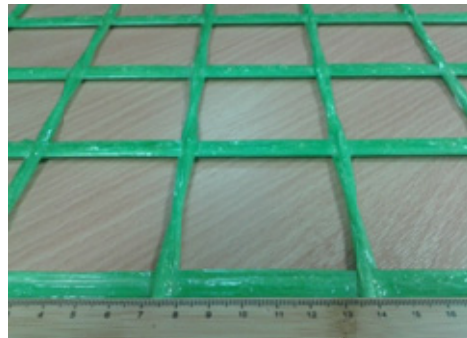
To determinate the effect of accelerated alkaline corrosion (aging) and cycles loads on the strength characteristics of the material, GFRP specimens have been subjected to different ageing treatments and fatigue tests to evaluate any decreases in their mechanical characteristics.

The coupon length were 190 mm with the clear distance between grips of approx. 90 mm. Specimens have been tested in tension, in accordance with ASTM D3039 (2014) standard, using an 'Instron Tensile Machine type 3382'. The machine was equipped with a load cell and an extensometer. To minimise stress concentration near the grip zone soft timber packing pieces (tabs) were glued with epoxy resin at both ends of the specimen. All tensile tests were conducted with cross-head speed of 0.50 mm/min (displacement control mode) at temperature of 23°C and humidity equal to 50%.

**Figure 1** GFRP grids: (a) type 1, and (b) type 2



(a)



(b)

#### *3.1 Untreated specimens*

From the test results, the tensile strength and the Young's modulus are calculated. 30 un-treated GFRP specimens were tested. The tensile strength is dependent of the kind of specimen because of the different ratio resin/fibre. The lowest measured tensile strength is 700.2 N/mm<sup>2</sup> which belongs to BC-type. Standard deviation and mean values were

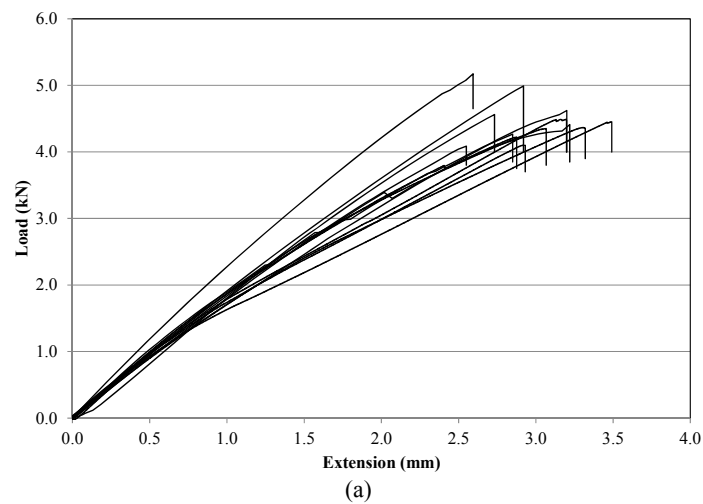
determined as given in Table 2. The three other types have a mean tensile strength higher than 950 N/mm<sup>2</sup>. During the tensile test, all GFRP coupons showed an approximately linear behaviour up to failure (Figure 2 (a)). The grid joint is a critical point because it presents of local deformation of the GFRP material (Figure 2 (b)).

These results have been reported exclusively for the purpose of qualitative evaluation of the decrease in the mechanical property due to the different treatments described in the following paragraphs.

**Table 2** Mechanical characteristics of the untreated GFRP specimens (SD = standard deviation)

<i>Index</i>	<i>No. of specimens</i>	<i>Max load</i>	<i>Tensile strength (SD)</i>	<i>Young's modulus E</i>	<i>Ultimate strain</i>
—	—	<i>N</i>	<i>N/mm<sup>2</sup></i>	<i>N/mm<sup>2</sup></i>	<i>%</i>
SC	7	3679	968.2 (85.93)	74,224 (3432)	1.30
BC	4	5321	700.2 (83.92)	72,236 (5655)	0.97
SR	14	4480	1179.1 (78.22)	70,189 (4210)	1.68
BR	5	8493	1117.6 (84.99)	74,453 (3122)	1.51

**Figure 2** (a) Load-extension curves for untreated SR-types specimens, and (b) GFRP grid joint

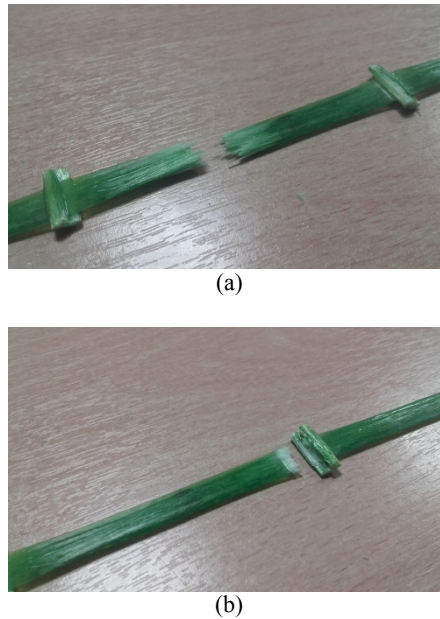


### *Durability of GFRP grids for masonry structures*

The average tensile capacity of the SC-type is  $968.2 \text{ N/mm}^2$  ( $\text{SD} = 85.93 \text{ N/mm}^2$ ). BC-type exhibits a tensile capacity of  $700.2 \text{ N/mm}^2$  ( $\text{SD} = 83.92 \text{ N/mm}^2$ ), SR-type shows a capacity of  $1179.1$  ( $\text{SD} = 78.22 \text{ N/mm}^2$ ) and BR-type exhibits a capacity of  $1117.6 \text{ N/mm}^2$  ( $\text{SD} = 84.99 \text{ N/mm}^2$ ).

Two different failure modes for untreated GFRP were noted: the first was a catastrophic collapse (tensile failure of the specimen approx. in the centre, Figure 3 (a)) and the second was a partial fibre failure at the GFRP grid joint (Figure 3 (b)). Failure henceforth was defined in this study as the point of the tensile load versus displacement (extension) curve where either sudden tensile load reduction was noted or a 20% reduction in load was detected in specimens with gradual post-peak load reduction. Both tensile strength and Young modulus were calculated using the dry glass fibre cross-section values ( $3.8$  and  $7.6 \text{ mm}^2$ , respectively, for GFRP grid Nos. 1 and 2). The coefficient of variation of the Young's modulus, defined as the ratio of standard deviation to mean, was significantly smaller compared to the one measured for the tensile strength. This is an expected behaviour due to the insignificant effect of the grid joint on this mechanical characteristic.

**Figure 3** Failure modes for SR specimens: (a) tensile failure in the centre, and (b) at the joint



### *3.2 Fatigue tests*

Fatigue tests were carried out on nine specimens prior to subjecting to tensile load. In addition, 14 untreated specimens were also tested for their tensile behaviour. Only SR-type specimens have been used for fatigue test (Table 3). For ease of identification, the specimens were nominated as SRU\_0 for the untreated and SRF\_1, SRF\_2 and SRF\_3 for the treated specimens subjected to load cycles of 60,000, 150,000 and 300,000, respectively. The specimens were tested in cyclic load using Instron Machine

E3000 (Figure 4 (a)). Loads were induced by a hydraulic piston and are subsequently transferred to the specimen through two clamping jaws and with a frequency of 7.5 Hz. This frequency value was chosen with the aim to reach the above number of load cycles in a limited time. It should also be noted that a frequency above 5 Hz may cause internal heating of FRP composites (Demers, 1998) and the frequency value has been chosen in order to study the material degradation. Fatigue tests are usually performed at a stress level larger than 50% of the material's tensile strength. In order to study the fatigue behaviour of the GFRP grids, stress level of about 60% of the material tensile strength was chosen corresponding to an axial tensile load of 2.5 kN. During the tests, the induced load values ranged from 1.5 to 2.5 kN (amplitude of the sinusoidal curve equal to 1 kN). A typical loading set-up for the specimens submitted to fatigue is shown in Figure 4 (b).

**Table 3** Characteristics of fatigue tests

<i>Index</i>	<i>No. of specimens</i>	<i>Section type</i>	<i>No. of cycles</i>
—	—	—	—
SRU_0	14	SR	0
SRF_1	3	SR	60,000
SRF_2	2	SR	150,000
SRF_3	4	SR	300,000

Specimens were subjected to tensile test to evaluate their tensile capacity and extension at failure after fatigue test. Failures occurred either through the complete split of the specimen at mid-point or at grid intersection. The tensile test results are reported in Table 4. The average tensile capacity of SR\_F\_1 is 1051.3 N/mm<sup>2</sup> (SD = 53.33 N/mm<sup>2</sup>), SR\_F\_2 exhibits a tensile capacity of 1133.9 N/mm<sup>2</sup> (SD = 55.26 N/mm<sup>2</sup>), SR\_F\_3 shows a capacity of 1088.9 (SD = 82.72 N/mm<sup>2</sup>) and the untreated specimens SR\_U\_0 exhibits an average tensile capacity of 1179.1 N/mm<sup>2</sup> (SD = 78.22 N/mm<sup>2</sup>).

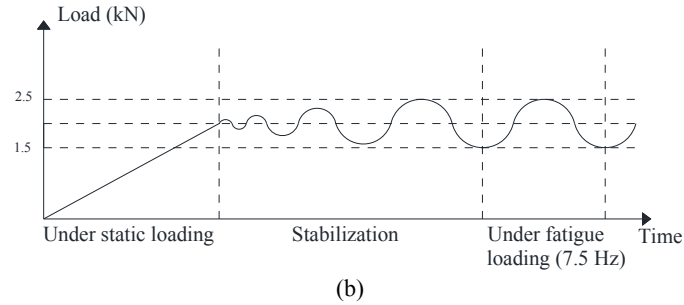
**Figure 4** (a) Fatigue test set-up, and (b) specimen loading set-up



(a)



**Figure 4** (a) Fatigue test set-up, and (b) specimen loading set-up (continued)

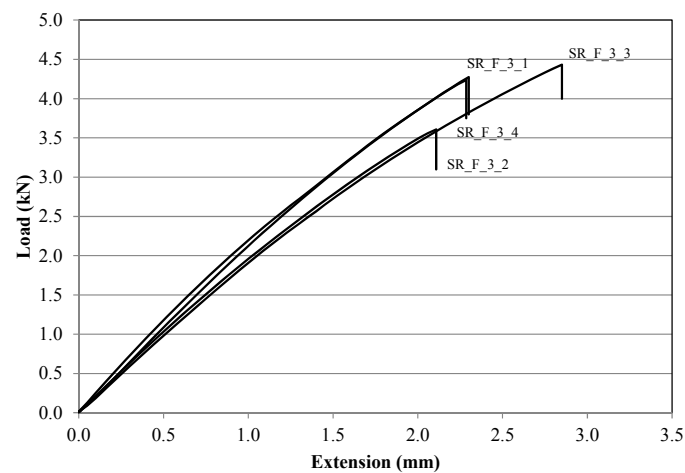


**Table 4** Mechanical characteristics of GFRP specimens subjected to fatigue treatments (SD = standard deviation)

<i>Index</i>	<i>Max load</i>	<i>Tensile strength (SD)</i>	<i>Ultimate strain</i>	<i>Strength decrease</i>	<i>Young's modulus decrease</i>
–	<i>N</i>	<i>N/mm<sup>2</sup></i>	<i>%</i>	<i>%</i>	<i>%</i>
SR_U_0	4480	1179.1 (78.22)	1.56	–	–
SR_F_1	3995	1051.3 (53.33)	1.41	10.8	6.7
SR_F_2	4309	1133.9 (55.26)	1.52	3.8	10.7
SR_F_3	4137	1088.9 (82.72)	1.26	7.6	1.1

This result shows an up to 10.8% decrease in the ultimate tensile strength of the tested specimens due to fatigue effect. However, it should be noted that no clear trend between the number of load cycles and reduction in ultimate tensile strength has been observed in this particular experimental campaign. The load-extension curves for varying number of load cycles during fatigue treatments are presented in Figure 5. Curves trend is characterised by almost perfectly linear behaviour up to failure with a sudden loss of load capacity post-failure.

**Figure 5** Load-extension curves for SR\_F\_3 specimens



### 3.3 Ageing treatments

The glass fibre, which is generally used in GFRP reinforcement, is susceptible to attack by OH-ions (Bagherpour, 2012). Therefore, an important task for the resin is to act as a barrier, defending the glass fibres from damaging agents. However, water and possibly alkalis will penetrate through micro-cracks or the un-cracked resin and eventually attack the fibres, the fibre/resin interface or the resin itself through plasticisation, hydrolysis and other mechanism of degradation, which may cause irreversible changes in the resin structure.

All four different types of GFRP samples (SC, BC, SR and BR) were subjected to ageing treatment. Two different environments were adopted to simulate possible field conditions: specimens were stored in deionised water and NaCl solution for different periods of time (one, two, three, five and seven months). The quantity of NaCl added was 35 g for 1 litre of water. After the treatments, samples were tested in tension to evaluate the effect of treatments on the tensile capacity. Tests were performed some days after the end of the ageing treatment. In order to remove its influence, the moisture content was kept at almost zero for both treated and untreated specimens. Tests have been carried out using the test set up introduced in Section 3. Table 5 shows various ageing treatments and the subsequent tensile test results: indices SW and W indicate treatment in NaCl solution and in deionised water, respectively, while the number after this index indicates the treatments time in months.

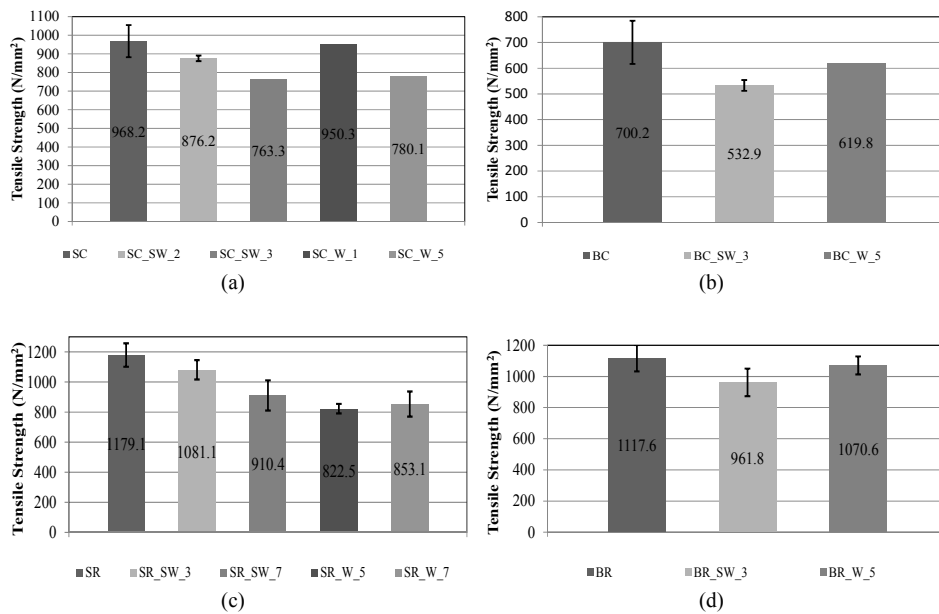
**Table 5** Test results of GFRP specimens subjected to aging treatments

<i>Index</i>	<i>No. of specimens</i>	<i>Treatment</i>	<i>Time</i>	<i>Max load</i>	<i>Tensile strength</i>	<i>Strength decrease</i>	<i>Young's modulus decrease</i>
–	–	–	<i>Months</i>	<i>N</i>	<i>N/mm<sup>2</sup></i>	<i>%</i>	<i>%</i>
SC	7	Untreated	–	3679	968.2	–	–
SC_SW_2	2	NaCl	2	3329	876.2	9.5	–2.09
SC_SW_3	1	NaCl	3	2900	763.3	21.2	11.02
SC_W_1	1	Water	1	3610	950.3	1.8	10.89
SC_SW_5	1	Water	5	2964	780.1	19.4	13.19
BC	4	Untreated	–	5321	700.2	–	–
BC_SW_3	2	NaCl	3	4049	532.9	23.9	28.48
BC_W_5	1	Water	5	4710	619.8	11.5	11.46
SR	14	Untreated	–	4480	1179.1	–	–
SR_SW_3	4	NaCl	3	4108	1081.1	8.3	5.55
SR_SW_7	7	NaCl	7	3459	910.4	22.8	7.68
SR_W_5	2	Water	5	3125	822.5	30.2	1.65
SR_W_7	9	Water	7	3241	853.1	27.7	3.83
BR	5	Untreated	–	8493	1117.6	–	–
BR_SW_3	5	NaCl	3	7309	961.8	13.9	9.05
BR_W_5	2	Water	5	8136	1070.6	4.2	0.42

### *Durability of GFRP grids for masonry structures*

Comparisons between tensile strengths for untreated and treated specimen for each type of sample are presented in Figure 6 (the over bar denotes standard deviation). It should be noted that limited number of specimens were testes for SC and BC series and results should be established by bigger experimental campaign. However, the emerging tendency seems quite interesting and confirmed by comparing these results with those obtained for other cross-sections types (SR and BR).

**Figure 6** Tensile strength: (a) SC-type, (b) BC-type, (c) SR-type, and (d) BR-type

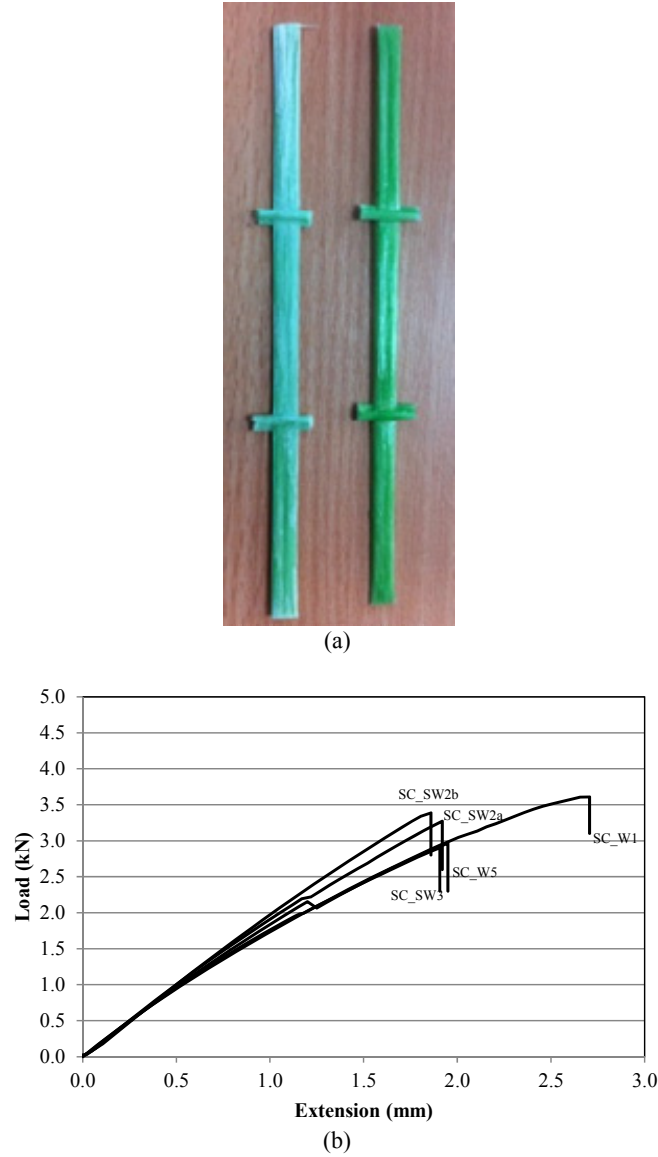


Specimens subjected to treatment in deionised water exhibited change in colour from green to white. This change became more evident with the increase of treatment duration. In contrast, specimens subjected to treatment in NaCl solution did not exhibit any change in colour (Figure 7 (a)).

The NaCl solution treatment for SC series produced a 21.2% decrease in the tensile strength after three months, while the deionised water treatment produced a slightly smaller decrease in tensile capacity of 19.4% after five months of immersion. Similar trend was noticed with the BC series; tensile capacity decrease of 23.9% and 11.5% were recorded after three months of immersion in NaCl solution and five months in deionised water treatment, respectively. Immersion in NaCl solution resulted in 22.8% decrease in the tensile strength of the SR series after seven months, while deionised water solution produced a 30.2% decrease in tensile capacity after five months.

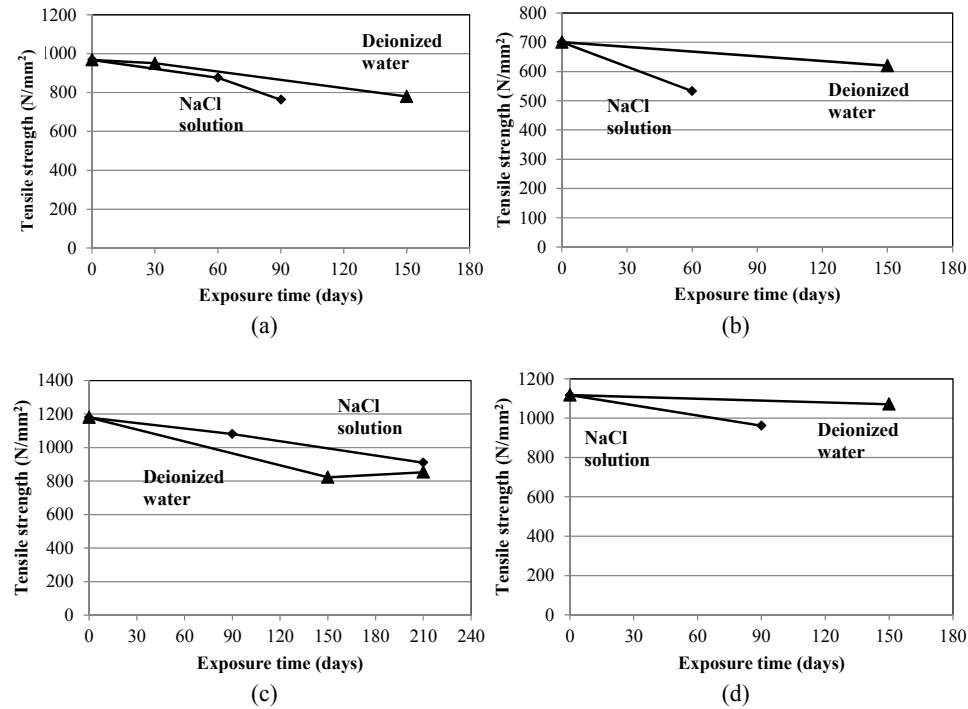
For the BR series, tensile capacity decrease of 13.9% after three months and 4.2% after five months were recorded when immersed in NaCl solution and deionised water, respectively. The rapid degradation of the mechanical characteristics of the material may be due to the direct exposure of specimens to strong ionic solutions. During the tensile test, all the GFRP specimens showed an approximately linear behaviour up to failure and failed through the rupture of fibres (Figure 7 (b)).

**Figure 7** (a) Specimen after ageing in deionised water and NaCl solution (from left to right, respectively), and (b) load-extension curves for SC specimens subjected to ageing treatment



Master curves for tensile strength retention versus exposure time at 23°C were obtained by fitting curve to the experimental data as shown in Figure 8. A clear trend of increased reduction in tensile strength with increase in exposure time in both NaCl solution and deionised water is established. However, due to limited experimental results these curves, in its present form, cannot be employed in the prediction of the tensile strength retention at any exposure time. Further experimental campaign, with larger data set, is required to establish such relationship.

**Figure 8** Tensile strength versus exposure time: (a) SC-type, (b) BC-type, (c) SR-type, and (d) BR-type



#### 4 Conclusions

This study analysed the durability behaviour of GFRP grids exposed to various environmental conditions. A series of experimental tests were performed in order to obtain insight into GFRP degradation mechanisms upon prolonged exposure to fatigue and ageing treatments. Tension-tension axial fatigue data for AR-glass FRP composites with limited frequency of fatigue load (7.5 Hz) without environmental concerns are summarised herein.

Specimens immersed in deionised water show a high decrease (27.7%) in tensile strength over the seven-month period of immersion. It is seen that immersion in deionised water causes a significant decrease in both the tensile strength and normal elastic modulus (Young's Modulus) of the GFRP. However, the decrease of Young modulus is smaller compared to tensile strength.

Tensile tests showed that GFRP specimens had a maximum retention of tensile properties of approx. 22.8% after immersion in a NaCl solution for seven months. However, for SC- and BC-type since the number of specimens tested was very limited and results should be confirmed by a larger experimental program. Test results are in line with researchers reports of degradation of the GFRP rebars or sheets varying from 10% to 47% depending upon the parameters selected for durability tests, viz. alkalinity,

moisture, temperature, stress and duration of the tests. The application of these materials for masonry retrofitting is not highly affected by this behaviour in consideration on the low stress level typical of masonry structures.

First results of fatigue treatment showed that fatigue did not produce significant damage in GFRP composites and residual physic-mechanical properties did not show a significant decrease in both tensile strength and Young modulus.

## Acknowledgements

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### *Durability of GFRP grids for masonry structures*

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*L. Righetti et al.*

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